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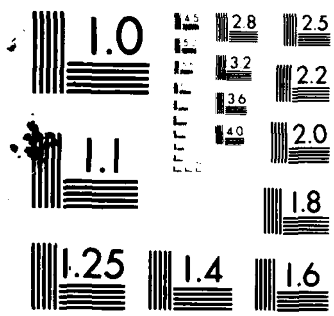

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PERSONNEL

The following scientific and technical personnel have been employed by the contract during part or all of the period covered by this report:

DR. SEELYE MARTIN, Co-Principal Investigator

DR. GARY MAYKUT, Co-Principal Investigator

DR. THOMAS GRENFELL, Research Associate

MR. PETER KAUFFMAN, Electronics Technician

MR. DONALD PEROVICH, Predoctoral Associate

MS. JANE BAUER, Predoctoral Associate

INTRODUCTION

During the past year, we have worked on the development of theoretical models which: (i) describe spatial and temporal variations in large scale heat exchange and ice production across the Arctic Basin, (ii) relate the optical properties of various types of first-year ice to the microstructure, (iii) simulate heat transfer and melting in summer leads, and (iv) investigate the growth of ice in wind-blown leads and polynyas. Experimental work included measurements of spectral absorption by pure ice, and observations of the growth of frazil ice in a wave field. Eleven papers have been published or are in press. During the fall, G. Maykut delivered several lectures on the heat and mass balance of the ice cover at the NATO/ONR symposium on air-sea-ice interaction at Maratea, Italy. We have been actively participating in efforts to develop an overall program for a marginal ice zone experiment (MIZEX). Earlier this year, S. Martin helped to prepare a refined MIZEX plan and has also assumed the principal role in organizing a MIZEX-type experiment in the Bering Sea.

Our interests in the MIZ are focused on problems related to the summer decay and retreat of the ice cover. This is a natural outgrowth of our previous work on (i) the interaction of shortwave radiation with the ice and upper ocean, and (ii) the effects of ice thickness variations on the regional heat and mass balance. Our present objectives are to identify the important thermal and mechanical processes in the summer MIZ, to measure and describe them through field observations, and to develop models and parameterizations of these local processes suitable for inclusion in larger scale models. The overall goal is a realistic model of the summer MIZ which can be incorporated onto GCM's and routine forecasting models.

DYNAMIC AND THERMODYNAMIC MODELING

Regional Heat and Mass Balance. In our past work we have examined how ice movement, by creating areas of open water and pressure ice, affects the large scale heat and mass balance of a sea ice cover. Ice motion data were obtained primarily from buoys and manned drifting stations in the Beaufort Gyre, while the thermodynamic input was based on drifting station climatologies. Although the results show that areas of young ice make a major contribution to the regional ice production and heat exchange in the Beaufort Gyre, we know little about contributions elsewhere in the Arctic Ocean. Ice movement and temperature data are, however, presently being gathered by an array of 15-20 data buoys, spanning much of the Arctic Basin and providing us with the potential to learn something about spatial variations in the large scale fluxes. We have therefore been working on techniques to utilize the buoy data for this purpose.

To accomplish this, we need to be able to calculate how the ice thickness distribution in each grid element changes with time, as well as to resolve temporal and spatial changes in each component of the heat and mass balance. A serious barrier to this effort is the lack of heat balance information - basically all we have to work with are observations of surface temperatures and climatological data on cloudiness and incident radiation. However, most of the fluxes are related either directly or indirectly to temperature, so it is possible to use the buoy temperatures and some climatological information in conjunction with parameterizations of the various fluxes to reconstruct the entire heat balance. Once this is done, strain information from the buoy array can be used to determine thickness variations and large scale heat exchange within different parts of the array. Research we have carried out during the past few years provides the framework necessary for this effort.

The first step was to obtain ice growth rates (as a function of time, location, and ice thickness) needed for the thickness distribution calculations. While our previously developed, simple ice growth model adequately describes thin ice, the growth of thicker ice depends more on the thermal history of the ice than on the surface heat balance at some particular time. A somewhat more complex model therefore had to be developed to keep track of temperatures within the ice. A series of simulations were carried out with this new model to determine the degree of temperature resolution required. The results show that the simple ice model causes growth rates to be overestimated during periods of cooling and underestimated during periods of warming, the effect becoming more pronounced as the ice becomes thicker. For example, predictions by the simple model differed by 20-30% from the more accurate model when H = 50 cm, but differed by 50% to several hundred percent when H = 300 cm. About 75% of the error could be removed by including a single internal temperature point, and about 95% by including three interior points. Three point resolution was chosen for the calculations. Numerical solutions with the three interior points agreed with analytical solutions to within 0.1-0.2°C.

After tests of the new ice model were completed, we began work on reconstructing the surface heat balance from the temperature observations. The ice model was used to specify the rate of heat conduction to the surface as a function of ice thickness, and the turbulent heat fluxes were expressed in terms of the difference between the known surface temperature and an unknown air temperature at the 10 m level. Incoming longwave radiation was parameterized in terms of this air temperature and cloudiness, the relationship being based on our previous radiation studies at Point Barrow, Alaska.

Finding a suitable method to estimate incident shortwave radiation proved unexpectedly difficult. An equation derived by Zillman (1972) gives approximate values of global radiation under cloudless skies for any latitude or season, and is frequently used in such studies. When daily radiation totals were compared with our observations from Barrow, we found that the Zillman formula underestimated the incident radiation by up to 10% between April and August. Monthly totals at various latitudes between 70-90°N showed similar differences. Less water vapor in the arctic atmosphere and backscattering of reflected radiation resulting from the large surface albedos probably explain the differences. When we tried to take into account the effect of clouds using an equation developed by Laevatsu (1960), we found that daily values were as much as 40% less than we observed at Barrow; monthly totals were underestimated by 15-20%. It appears that the Laevatsu formula describes thicker, lower latitude clouds. This points up the need to develop expressions for incident shortwave radiation and the effects of cloudiness which are designed specifically for conditions found in the Arctic. With an 18% correction, however, the equations of Zillman and Laevatsu were found to provide values of incident radiation in reasonable agreement with observations. Cloudiness was specified in each region from the data of Vowinckel and Orvig (1962).

The surface heat balance equation was solved for air temperature, which then allowed the calculation of heat fluxes over all thicknesses of ice. Calculations were carried out between March 1979 and March 1980. During the spring of 1979, inferred temperatures and area-weighted fluxes were entirely consistent with drifting station averages. Monthly totals of ice production and turbulent heat exchange varied by up to 40% across the basin, being somewhat correlated with latitudinal differences in incident shortwave radiation. The amount and timing of summer melting was also reasonable. During the fall of 1979 and winter of 1980, temperatures were much warmer than would be expected on the basis of climatological averages. This sugge ed that the buoys might be covered by snow, and subsequent analysis of diurnal temperature variations seem to bear this out. Unless some method can be developed to take into account the snow cover, it appears that the fall and winter buoy temperatures will not be useful for the heat balance calculations. Tests are underway in our coldrooms to learn more about the temperature response of these buoys.

Another problem is how well large scale strains calculated from the buoy motions are correlated with local opening and closing. We suspect that the large scale average strains tend to seriously underestimate the amount of deformational activity within a particular region. Dr. A. Thorndike at the Polar Science Center, University of Washington, is presently looking into this question. On a related topic, we are trying to learn how sensitive the large scale fluxes are to various properties of the strain field. Drifting station strain records indicate that very large differences in the average divergence do not necessarily produce a large effect on the regional heat exchange. It appears that it is the variability of the motions that is most important to the heat exchange. On the other hand, the magnitude of the time averaged strain <u>is</u> important to the mass balance. Additional sensitivity studies are needed before we can understand more precisely how different aspects of the strain field affect the regional fluxes.

Despite the remaining questions and problems, our general approach to the problem appears to work. What we need most are improvements in the input data: temperatures unbiased by the snow (obtained with satellite sensors or by improved buoy design, e.g. the Norwegian buoys), daily cloud averages across the Arctic from satellite observations, more appropriate parameterizations for incoming shortwave radiation and the effects of clouds, and a better understanding of the relationship between large scale and small scale strains. Substantial improvements in these areas should be forthcoming during the next few years. Application of these ideas to the MIZ seems feasible and should be tested during the coming MIZEX program.

Summer Ice Decay. Our regional calculations indicate that the amount of shortwave radiation absorbed by the ocean in areas of perennial ice is sufficient to decrease the average ice thickness by over 10%, and to decrease the ice concentration by 6-10%. In areas of seasonal ice, positive feedback from increasing amounts of open water, combined with thinning, result in complete disappearance of the ice cover during the summer. To study the role of solar radiation in the overall decay of the ice, we constructed a simple model of heat transfer in leads and used it to simulate the behavior of an ice cover with various idealized lead geometries. Both seasonal and perennial ice were examined. Results from this work have been written up as a draft entitled "On the Role of Shortwave Radiation in the Decay of a Sea Ice Cover" which will be submitted for publication in the Journal of Glaciology.

In the above work we assumed that ice movement and mechanical processes would keep the water in the lead well mixed, greatly simplifying the numerical treatment of the problem. While few pertinent data are available, we have located some scattered Soviet observations. They report the presence of both horizontal and vertical temperature gradients in a 1 m thick layer of "fresh" water at the surface of a summer lead. Vertical gradients were 15 times larger than those in the horizontal. Strong stability in the vertical seems inconsistent with the depth dependent input of shortwave energy into a layer of fresh water near the freezing point, so we presume that the reported "fresh" water actually had a stabilizing salinity gradient. This gradient could be as small as .16 $^{o}/oo$ per meter. The article does not tell how typical the observations are, nor are we given information about the general conditions (water salinity, lead width, solar input, temperature gradients near the ice walls, wall profiles, etc.), but the data do indicate that the well mixed assumption may represent an over-simplification and that a closer examination of the processes involved in heat, salt, and water transport in leads are necessary.

For this reason we have constructed a two-dimensional, time-dependent model of heat diffusion in a lead. Radiative heating of the water is treated as a depth dependent source term. An energy balance equation, depending on meteorological conditions, supplies the surface boundary condition. A system of equations is solved simultaneously to determine temperatures in the lead and in the water beneath the ice and lead. At present heat fluxes to the ice walls are calculated from horizontal temperature gradients, then used to determine lateral ablation rates. Values of vertical and horizontal diffusivities can be specified independently in both water layers. The effects of various heat transport processes can be approximated through suitable selection of these diffusivities.

Although our numerical experiments with this model are still in the early stages, we have carried out runs using a range of diffusivities. The results show that conduction alone is inadequate to explain heat transport in summer leads. With only conduction, lead temperatures rose to over 8°C during a 10 day period, yielding lateral ablation rates only 1% as large as in the well mixed case. More realistic diffusivities yielded lateral melt rates on the order of 20 cm/day near the surface and 5 cm/day near the bottom edge of the floe. Lead temperatures were only a few tenths of a degree above the freezing point, but some vertical and horizontal structure was evident. Towards the center of the lead the temperature variation was greatest in the vertical, while near the ice edge most of the temperature structure was due to horizontal changes. Increasing the vertical mixing caused a decrease in the rate of lateral melting, slightly more bottom melting, and heat storage in the ocean. Calculations were performed to determine the time required for a lead to reach quasi-steady state conditions. For a 100 m lead realistic diffusivities yielded "warm up" times on the order of 1 to 2 days with the length of this period being inversely proportional to the diffusivity.

A recent series of numerical experiments focused on the heat content of the water immediately below a perennial ice cover. It was assumed that this water was overlain by a mixture of moving floes and leads. When under open water the lower region gained heat by absorbing shortwave radiation and when under a floe it was cooled by losing heat to the ice. The calculations indicate that for typical values of vertical diffusivity and ice velocity, horizontal gradients in the lower region are much smaller than those present in the upper lead. To a good approximation the lower region can be considered horizontally homogeneous, greatly simplifying the numerical treatment of the problem. We are currently looking at the situation in the MIZ where ice concentrations are substantially smaller. We are also attempting to improve the treatment of heat exchange in the boundary layer between the water and the ice and by allowing the eddy diffusivity to vary spatially. The model should provide a useful framework for studying a variety of lead problems. We expect to be able to use it in analyzing planned field observations, in evaluating the effects of various heat transfer processes, and in understanding the impact of heat storage in the ocean on the mass balance of the ice pack.

RADIATIVE TRANSFER STUDIES

Our laboratory studies have provided us with a better understanding of the optical properties of sea ice and of their response to the environmental factors which influence ice structure. We have found that, since the absorption coefficients of brine and pure ice are essentially independent of temperature, the albedo and transmission properties of young sea ice are governed primarily by the platelet structure. Enhanced scattering results in higher albedos. It also increases the extinction coefficients because it increases the optical path length thereby causing greater absorption within the ice. The amount of scattering is dependent on temperature. With increasing temperature, brine pockets and channels open up and the brine/ice interfaces coalesce and become more rounded, lowering the scattering cross sections and decreasing the density of the scattering inhomogeneities. If the ice temperature drops below the eutectic point, salt crystals are precipitated out of solution causing a sudden rise in the scattering. The resulting albedos are similar to those of snow. Growth rate is also important because it determines the initial crystal sizes, platelet spacings, and distribution of brine in the ice, conditions which persist throughout the first yearly cycle. Spectral albedos are also influenced by changes in surface conditions. Wetting of the surface due to melting or expulsion of brine upon cooling gives a smooth surface and lowers the albedo. Formation of salt flowers or melting followed by brine drainage leaves an uneven crumbly surface with a higher albedo. A detailed description of the laboratory experiments and the results outlined above has been published in the latest issue of the Journal of Glaciology.

A preliminary theoretical analysis of the results mentioned above was also carried out using a four stream discrete ordinates model. Variations in albedo and transmittance were related to changes in the single scattering albedo, the angular distribution of scattering by small elements of ice (the phase function), and surface scattering. One and two layer models were compared to the observations using absorption coefficients derived from the results of Sauberer (1950) and adapting a representative phase function from the results of our scattering experiments. The scattering efficiency was treated as an adjustable parameter to fit the observed spectral albedos at 650 nm. Calculated transmittances at 650 nm were then compared with observations. The difference between theory and observation varied from 0.6% to 55%. Best agreement was obtained for warm homogeneous ice, and the differences increased for colder more rapidly grown ice. The poorer agreement for cold ice points out the importance of vertical variations in the ice structure resulting from brine volume gradients and growth rate decreases with ice thickness. A precise treatment of the problem will thus require a model which has more than two layers.

To test model predictions of the wavelength dependence of the optical properties of the ice, spectral albedos (α_λ) and transmissivities (T_λ) were calculated for the homogeneous ice cases. The scattering cross sections were taken to be independent of wavelength as suggested by theoretical considerations as well as by our scattering measurements. Agreement with observations for both α_λ and T_λ was quite good. Differences in T_λ ranged from 0 to 10% with predicted T_λ's tending to be too large at shorter wavelengths. Since the wavelength dependence of the transmittance is determined primarily by the spectral absorption coefficients, we suspect that the observed deviations indicate that inaccuracies may be present in the absorption coefficients of Sauberer. A paper describing the analysis in detail has been accepted for publication by the Journal of Glaciology.

Although the magnitudes of the spectral absorption coefficients for pure ice (k_λ) at visible wavelengths are small, they specify α_λ and T_λ in the models and strongly affect predictions of the amount of shortwave radiation absorbed in ice and snow. Values of k_λ are also very important for calculating the energy balance in terrestrial ice clouds and for a number of extraterrestrial applications. The best available data until now between 400 and 900 nm are those reported by Sauberer. However, because the absorption is so small at visible wavelengths and because Sauberer had available rather thin ice samples, his data are only accurate to one or two significant figures. In view of inconsistencies which have appeared in our comparisons of observational and theoretical results and because of similar difficulties encountered by other investigators in modeling albedos of snow, we initiated an experiment to determine k_λ at visible and near-infrared wavelengths with improved precision.

The optical measurements were made with the new scanning photometer to obtain higher spectral resolution. To increase the absolute accuracy of measured k_λ values, large samples of bubble-free ice were produced. We employed the stirring technique developed several years ago in our laboratory and were able to grow a single block of clear fresh bubble-free ice 2.8 m long and 20 x 20 cm in cross section. This gave sufficient beam attenuation at visible wavelengths to achieve three figure accuracy in k_λ. Because the ice acted as a light pipe, little if any of the light scattered internally from crystal boundaries was lost through the sides of the block so that the only beam attenuation came from true absorption. At wavelengths between 1000 and 1400 nm the results agreed very well with previous data, but differences appeared at shorter wavelengths which increased gradually to a maximum between 400 and 600 nm.

Because of the higher spectral resolution and the much greater optical path length through the ice, the present values are at least an order of magnitude more accurate than the results of Sauberer. We have detected new spectral features which are consistent with those for k_λ (water) plus an absorption minimum at 470 nm instead of 400 nm, again in better agreement with the results for water. Although we have not yet checked quantitatively, it also appears that the new results will improve the accuracy of our theoretical predictions for albedos and transmittances. A paper describing the experiment has been published in the August issue of the Journal of Geophysical Research.

The principal limitations of the four stream model are the approximations needed to include refraction at the air-ice boundary and the requirement that the phase function be represented by a marginally accurate four term series expansion. In addition, the scattering coefficient is treated as an adjustable parameter to fit the observed albedos rather than being calculated from the ice structure. To avoid these problems, we are using a 16 stream model. Refraction at the surface and at layer interfaces has been rigorously included, and because 16 terms are used in the expansion of the phase function, scattering is represented to better than 1% accuracy.

The major difficulty with the 16 stream model has been an instability which occurs during the iterative solution for the characteristic functions at visible wavelengths where absorption is very weak compared to scattering. By reformulating the problem, however, we have developed an alternate method which avoids iteration entirely and gives accurate solutions for all cases we have investigated so far. Since the technique is not sensitive to the ratio of scattering to absorption, it works even for the extreme case of sea ice below the eutectic point. Because the problem of scattering and absorption in media containing highly scattering transparent spheres is common in other fields, we have submitted a description of this method for publication to the Journal of Quantitative Spectroscopy and Radiative Transfer.

In addition we have recently incorporated the technique suggested by Stamnes and Swanson (1981) to solve for the eigenvalues of the characteristic equation. This gives a significant improvement in computing efficiency over the iterative method used previously and yields the same order of accuracy.

The model can now determine directly scattering and absorption in ice from the density and distribution of bubbles and brine pockets. For first-year ice, we can also derive these distributions from the temperature, bulk salinity, ice density, and initial growth conditions. Thus the optical properties of the ice can be calculated from these more easily measurable macroscopic quantities. Because summer melting, recrystallization, and bulk deformation can alter the ice structure, additional considerations will be needed for multiyear ice.

The present model assumes that structural inhomogeneities scatter as "equivalent spheres" whose scattering properties can be obtained from Mie theory or ray optics. The number density of brine inclusions is determined from the initial brine volume and the platelet spacing, both of which can be calculated from the initial growth rate using formulae from Weeks and Lofgren (1967) and Lofgren and Weeks (1969). The total volume of vapor in the ice can then be obtained from the ice density, and by assuming the exponential bubble size distribution of Gavrilo and Gaitshkhoki (1971), the bubble density can be determined. Our own measurements of first-year ice at T-3 appear to confirm the Gavrilo and Gaitshkhoki distribution.

The dependence of brine pocket size and number density on temperature during the initial cooling stage is determined from the brine volume in conjunction with a surface energy instability which causes brine channels to collapse into strings of spheres. The spacing of the spheres is determined by the character of the instability and the diameter of the brine channels; radius of the spheres is specified by the bulk brine volume.

Our present calculations assume a single homogeneous layer, and although the laboratory studies indicate that multilayer models will be necessary to match field data in detail, our initial results are quite encouraging. For example, the predicted asymptotic extinction coefficients for thick ice (1 to 3 m) are approximately 0.012 to 0.017 cm^{-1} in the visible which gives integrated values in excellent agreement with Untersteiner (1961) and Grenfell and Maykut (1977). We find that brine pockets appear to be dominant scatterers because their volume density is so high. This is supported by our qualitative observations of sea ice and bubbly glacier ice. Because of the high scattering efficiency due to the large density of brine inclusions, the optical depth of 1 m thick ice at 500 nm is on the order of 300. However, since the brine pockets are very strongly forward scattering due to their low optical contrast with the ice, the resulting transmissivities are still on the order of 8 to 10 percent. This is much higher than would normally be expected for so large an optical depth; however, transmissivities on this order are quite close to what we have observed for natural sea ice. Predicted bulk albedos are about 0.6 to 0.65 which is consistent with results from remote ice stations. Our recent measurements of spectral albedos at Point Barrow are somewhat lower at visible wavelengths though, suggesting that enhanced levels of impurities such as dust or soot are present in the sea ice near shore. Since Langleben (1969 and 1971) also observed depressed albedos in the Canadian archipelago, this may be a general effect around the margins of the Arctic Basin rather than a local phenomenon near Point Barrow.

The spectral dependence of albedo and transmittance in the infrared do not yet agree very well with observed values. This is probably due to surface roughness effects and will be examined later using multilayer analyses.

We are presently working on a parameter study to determine how the optical properties of homogeneous single ice layers respond to variations in thickness, temperature, salinity, initial growth conditions, and bubble density. Both initial growth conditions and bubble density are important in the visible and near infrared. For example, increasing the growth rate from 0.7 to 7 cm per day results in a 20% increase in the albedo at 500 nm (α_{500}); decreasing the ice density from about 0.92 gm/cm^3 (the no-bubble case) to 0.86 gm/cm^3 raises α_{500} from 0.57 to 0.85. Both results are in qualitative agreement with our observations.

Surprisingly the effect of initial cooling in newly formed sea ice is quite small. Contrary to our expectation that the albedo should increase, the model predicts that it is nearly constant as long as the temperature is above the eutectic point. This is because the formation of large numbers of brine pockets from a few brine channels is compensated by the small size of the brine pockets due to the decrease in brine volume. This suggests that the albedos of cold winter ice should remain fairly constant even though both spatial and temporal variations in temperature are present. When the ice temperature falls below the eutectic point, however, the density of scattering centers increases by 2 1/2 orders of magnitude and α_{500} approaches one.

If the ice undergoes subsequent warming, additional processes such as coalescing of the brine pockets and brine drainage must be taken into account. Preliminary computations suggest that these processes do produce a systematic decrease in albedo with warming which agrees with the laboratory results mentioned earlier and with our field observations.

When the parameter study is completed, we plan to model the optical properties of different ice types for which we have observational data, using the results from T-3, Point Barrow, and Prudhoe Bay. We will try to relate small scale ice structure to the optical observations for each of the different ice types.

MARGINAL ICE ZONE STUDIES

Our research during the past year involved work in the following three areas. First, in cooperation with BLM/NOAA, we carried out a field study of the formation and decay of ice bands at the Bering Sea ice edge, using radar transponder buoys developed on the present contract. Second, S. Martin worked on the preparation of two documents describing possible experiments in the Marginal Ice Zone (MIZ). Third, a graduate student, Jane Bauer, developed a model of frazil and grease ice growth in a wind-swept lead.

The field experiment was carried out from the NOAA ship SURVEYOR and focused on the formation, translation, and decay of ice bands which occur near the edge of the ice pack. These bands consist of small, broken ice floes which form at approximately right angles to the wind, and measure about 1 km in width by 10 km in length. Results from the tracking of the radar transponders show that the bands are accelerated away from the interior ice by the absorption and reflection of wind waves. We found that the momentum transferred to the ice bands from the waves causes them to move with velocities 40% greater than that of a satellite buoy in the ice interior. We also found that as the bands move into warmer water, they melt in two ways. First, the ice floes in the band become thinner by classic bottom melting. Second, the bands decrease in width when the wind-waves break on the upwind edge, cracking the large floes into small pieces. Because ice floes are only good reflectors if their diameter is greater than half the incident ocean wave length, once the floes are broken they absorb less wave momentum. Thus the small floes experience less force than the large floes, so that they drift upwind relative to the larger floes.

Once the small floes drift upwind, because their surface-to-volume ratio is greater than that of the large floes, they rapidly melt in the surrounding water. Finally, the drifting away and melting of these small floes exposes new large floes to the breaking waves so that the process continues. Therefore, as the bands drift downwind, they decrease in both thickness and width until they ultimately melt away. A description of these results will be presented in preliminary form at the December AGU meeting in San Francisco.

During the past year S. Martin worked on the preparation of two documents describing possible experiments in the MIZ. The first was a general background document on MIZ experiments in the Northern Hemisphere titled "MIZEX: A Program for Mesoscale Air-Ice-Ocean Interaction Experiments in Arctic Marginal Ice Zones" by Wadhams, Martin, Johannessen, Hibler, and Campbell. The second was a specific field plan for a Bering Sea ice deformation experiment with the working title "Field Plan for the 1983 Bering Sea MIZ Ice Deformation Experiment"; this document should be available for distribution in January 1982.

Jane Bauer, a graduate student, is doing a laboratory and numerical model of ice growth in wind-blown leads and polynyas. Her model is designed to apply near islands and coastal areas in the Bering Sea where wind blows off the land and semi-permanent areas of open water exist. Within these regions there is a high rate of ice production and an accompanying oceanic salt flux which may contribute to the generation of the deep water in the Arctic Ocean.

Her present work involves a one-dimensional model of frazil ice growth such as we have observed to occur in 100 m wide arctic leads. In this case the wind blowing across the lead raises waves and strongly agitates the water. The combination of the agitation and the cold air leads to frazil ice growth, then the wind waves herd the ice to pile up on the downwind side to depths of 0.1-0.3 meters. As time progresses, the ice cover on the lead advances upwind and may eventually cover the entire lead. In Bauer's model, the rate of ice advance and ice depth are given as functions of wind speed, air temperature, and solar radiation. The model will also predict the oceanic salt flux. Bauer is presently writing up a description of the model for publication in the Journal of Geophysical Research and will also present it at the San Francisco AGU meeting.

REFERENCES

Gavrilo, V. P. and B. Ya Gaitshkhoki, The statistics of air inclusions in ice, in The Physics of Ice, V. V. Bozorodskii, ed., 125-128, 1971.

Grenfell, T. C. and G. A. Maykut, The optical properties of ice and snow in the Arctic Basin, Journal of Glaciology, 18, 445-463, 1977.

Laevatsu, T., Factors affecting the temperature of the surface layer of the sea, Commentationes Physico-Mathematicae, 25:1, 8-134, 1960.

Langleben, M. P., Albedo and degree of puddling of a melting cover of sea ice, Journal of Glaciology, 8, 407-412, 1969.

Langleben, M. P., Albedo of melting sea ice in the Southern Beaufort Sea, Journal of Glaciology, 10, 101-104, 1971.

Lofgren, G. and W. F. Weeks, Effect of growth parameters on substructure spacing in NaCl ice crystals, Journal of Glaciology, 8, 153-164, 1969.

Sauberer, F., Die spektrale Strahlungsdurchlässigkeit des Eises, Wetter und Leben, 2, 193-197, 1950.

Stamnes, K. and R. A. Swanson, A new look at the discrete ordinate method for radiative transfer calculations in anisotropically scattering atmospheres, Journal of the Atmospheric Sciences, 38, 387-389, 1981.

Untersteiner, N., On the heat and mass budget of arctic sea ice, Archiv für Meteorologie, Geophysik und Bioklimatologie, A, 12, 151-182, 1961.

Vowinckel, E. and S. Orvig, Cloud Amount and Type over the Arctic, 27 pp., Publication in Meteorology No. 51, McGill University, Montreal, 1962.

Weeks, W. F. and G. Lofgren, The effective solute distribution coefficient during the freezing of NaCl solutions, in Physics of Snow and Ice, H. Oura, ed., Int'l Conf. of Low Temperature Science Proceedings, Vol. 1, pt. 1, Sapporo, 579-599, 1967.

Zillman, J. W., A study of some aspects of the radiation and heat budgets of the southern hemisphere oceans, Meteorological Studies, 26, 562 pp., Bureau of Meteorology, Department of the Interior, Canberra, Australia, 1972.

REPORTS PUBLISHED AND IN PRESS

1. Bauer, J. and S. Martin, Field observations of the Bering Sea ice edge properties during March 1979, Monthly Weather Review, 108(12), 2045-56, 1980.

   During March 1979 field observations in the Bering Sea show that because of the interaction of winds and ocean swell with the ice, the ice edge divides into three distinct zones. First, adjacent to the open ocean is an "edge" zone, 1-15 km in width, which consists of heavily rafted and ridged floes with thicknesses of 1-5 m and measuring 10-20 m on a side. Second is a "transition" zone measuring ~5 km in width, which consists of rectangular ice floes with thicknesses of ~0.5 m and measuring 20-40 m on a side. Third is the "interior" zone, which extends over hundreds of kilometers and consists of very large, relatively flat floes with thicknesses of ~0.3 m. In the edge zone the incident swell causes the floes to fracture, raft and form pressure ridges, resulting in small thick floes. In the transition zone the swell amplitude is reduced to the point that the floes fracture in a rectangular pattern with very little rafting or ridging taking place. In the interior zone the swell amplitude is further reduced such that the waves propagate without fracturing the ice, so that the floes have horizontal dimensions of kilometers. Because of this ice distribution, when strong winds blow off the ice, bands of ice floes form at the ice edge. The reason bands form is that the edge zone ice has a large aerodynamic drag due to the heavy rafting and ridging, so that this ice moves downwind ahead of the rest of the pack. Once this ice moves away from the pack, the combination of aerodynamic drag plus the absorption of wind wave and swell energy leads to the band formation. We observed that these bands, which are on the order of 1 km wide and 10 km in length, move south into warmer water until they melt.

2. Grenfell, T. C., A visible and near infrared scanning photometer for field measurements of spectral albedo and irradiance under polar conditions, Journal of Glaciology, 27(97), 476 - 81 , 1981.

   The design and operating characteristics are presented for a visible and near infrared scanning photometer which can measure incident and reflected spectral irradiance from 400 nm to 2450 nm. The instrument is designed to record over 98% of the solar radiation incident upon and reflected from the Earth's surface using a turret-type collector and a circular variable interference filter. The apparatus has been tested successfully on Arctic sea ice at temperatures down to -20°C. It is self-contained and easily portable, and its mass is less than 16 kg. Some preliminary results are presented.

3. Grenfell, T. C. and D. K. Perovich, Radiation absorption coefficients of polycrystalline ice from 400-1400 nm, Journal of Geophysical Research, 86(C8), 7447-50, 1981.

Absorption coefficients have been measured for bubble-free polycrystalline ice over the spectral region 400-1400 nm. In order to obtain an easily measurable attenuation at short wavelengths (400-500 nm), a 2.83 m block was used. The technique employed to grow large quantities of bubble-free ice is presented in detail. The absorption coefficients agree very well with previous results in the infrared and appear to provide greater accuracy and spectral detail at visible wavelengths.

4. Grenfell, T. C., D. K. Perovich, and J. A. Ogren, Spectral albedos of an alpine snowpack, Cold Regions Science and Technology, 4, 121-27, 1981.

Spectral albedos (α_λ) from 380 to 2500 nm are reported for a snowpack in the Cascade Mountains of Washington. Data were obtained from just after an 0.4 m snowfall on 13 March 1980 until the pack had metamorphosed to melting coarse grains about 1 mm in diameter mixed with dust. Measurements were made under cloudy conditions to obtain a diffuse incident radiation field. Structural parameters of the snow were measured concurrently for all cases, and on three occasions, estimates of absorbing impurity content were obtained. The dependence of the spectral albedos of the snowpack on grain size and impurity content is illustrated. Comparison of wavelength-integrated albedos (α_{obs}) obtained using Kipp and Zonen radiometers with corresponding albedos derived from α_λ data show good agreement, and suggests a correlation between α_{obs} and the amount of incident radiation transmitted by the cloud layer. Comparison with theoretical models confirms that impurities in the snow depress α_λ at visible wavelengths but have little effect beyond 900 nm in the infrared; however, quantitative agreement with theory is uncertain at present.

5. Josberger, E. G. and S. Martin, A laboratory and theoretical study of the boundary layer adjacent to a vertical melting ice wall in salt water, Journal of Fluid Mechanics, 111, 439-73, 1981.

In an experimental and theoretical study we model the convection generated in the polar oceans when a fresh-water ice wall melts in salt water of uniform far-field temperature T_∞ and salinity S_∞. Our laboratory results show that there are three different flow regimes which depend on T_∞ and S_∞. First, when T_∞ and S_∞ lie between the maximum density curve and the freezing curve, the flow is only upward. Secondly, for the oceanic case

$30 \leq S_\infty \leq 35$ $^o/_{oo}$ and $T_\infty < 20°C$, the flow consists of a laminar bidirectional flow at the bottom of the ice and a turbulent upward along the remainder of the ice wall. The laminar flow consists of an upward flowing layer approximately 2 mm thick inside of a downward flowing outer layer approximately 10 mm thick. Thirdly, for the same range of S_∞ but for $T_\infty > 20°C$, the flow reverses: at the top of the ice there is a laminar bidirectional flow above a downward turbulent flow. To model the turbulent upward flow theoretically, we numerically solve the governing equations in similarity form with a spatially varying eddy diffusivity that depends on the density difference between the ice-water interface and the far-field. The laboratory data then allows us to evaluate the dependence of eddy diffusivity on T_∞ and S_∞. The results show that the magnitude of the eddy diffusivity is of the same order as the molecular viscosity and that both mass injection at the interface and opposed buoyancy forces must be included in a realistic flow model. Finally, we use an integral approach to predict the far-field conditions that yield the high-temperature flow reversal and obtain a result consistent with our observations.

6. Martin, S., Frazil ice in rivers and oceans, Annual Reviews of Fluid Mechanics, 13, 379-97, 1981.

This paper is a critical review of field observations, laboratory experiments, and theoretical models of the formation and growth of river and ocean frazil ice.

7. Martin, S. and P. Kauffman, A field and laboratory study of wave damping by grease ice, Journal of Glaciology, 27(96), 283-313, 1981.

In a field and laboratory study we discuss the formation, growth, and wave-absorption properties of grease ice. Our field observations show that grease-ice formation occurs under cold windy conditions in both leads and polynyas. In leads grease ice forms in the open water, then is herded to the down-wind edge of the lead; in polynyas a Langmuir circulation herds the grease ice into long plumes parallel to the wind. In the laboratory we grow grease ice in a wave tank and measure its wave absorption properties for single-frequency, two-dimensional waves. On a large scale we find that the thickness of the grease ice, which increases away from the paddle, is determined by a balance between the wave-momentum flux and the free-surface tilt. On a small scale our photographs show that the crystals which make up the grease ice consist of discs measuring about 1 mm in diameter and 1-10 μm thick, which at low rates of shear sinter together into larger clumps yielding a viscosity increase. To measure this nonlinear viscosity, we study the decay of wave amplitude between two critical distances measured inwards from the leading edge. The first occurs when the depth of grease ice exceeds

k^{-1} where k is the wave number; the second further distance is a line of transition from liquid to solid behavior which we call the dead zone. Between these two distances the wave amplitude decays with a linear slope, α, which increases as $(a_0k)^2$ where a_0 is the wave amplitude in open water. Concurrent measurements of ice concentration show that it increases from values of 18-22% at the leading edge to a local maximum of 32-44% at the dead zone, while the values at the dead zone increase nonlinearly with a_0k. Finally, comparison of the observed α to that calculated from a yield-stress viscosity model shows if the yield-stress coefficient is proportional to the incident wave-momentum flux, the model predicts the observed α.

8. Perovich, D. K. and T. C. Grenfell, Laboratory studies of the optical properties of young sea ice, Journal of Glaciology, 27(96), 331-46, 1981.

Laboratory experiments were performed to determine the optical properties of young salt ice and to examine correlations between the optical properties and the state of the ice. Ice was grown at different temperatures (-10, -20, -30, and -37°C) from water of different salinities (0, 16, and $31^o/_{oo}$). The experiments were conducted in a cylindrical tank 1 m in diameter designed to approximate natural ice growth and to permit in situ optical measurements. Observed incident, reflected, and transmitted irradiances were used in conjunction with a modified Dunkle and Bevans photometric model to determine spectral albedos and extinction coefficients. Cold ice only 0.25 m thick had albedos which were comparable to the values for 2 to 3 m multiyear ice examined by previous researchers during the summer melt season; extinction coefficients were 1.5 to 15 times greater. As the ice temperature and hence brine volume decreased, both albedo and extinction coefficient increased; when the ice temperature dropped below the eutectic point, they increased sharply. In addition, ice grown at lower air temperatures had greater albedos and extinction coefficients even when ice temperatures were the same. Variations in the optical properties of the ice are determined by changes in the amount of brine and its distribution; thus the optical properties of salt ice depend not only on ice temperature but on initial growth rate. Variations in ice salinity over the range $4^o/_{oo}$ to $14^o/_{oo}$ produced no detectable changes in the optical properties.

9. Wadhams, P., S. Martin, O. M. Johannessen, W. O. Hibler, and W. J. Campbell, MIZEX, A Program for Mesoscale Air-Ice-Ocean Interaction Experiments in Arctic Marginal Ice Zones: I. Research Strategy, 20 pp., CRREL Special Report 81-19, June 1981.

This document describes the research strategy for a series of mesoscale studies of Arctic marginal ice zones. The main goal of this program is to gain a better understanding of the processes occurring at the ice margin. These processes are relevant to climate, weather forecasting, petroleum exploration and production, marine transportation, naval operations, and commercial fisheries. In addition, MIZEX will aid in determining what modifications to existing ice-ocean-atmospheric models are needed for better prediction near the ice margin.

10. Perovich, D. K. and T. C. Grenfell, A theoretical model of radiative transfer in young sea ice, Journal of Glaciology (in press).

11. Maykut, G. A., Surface heat and mass balance, in Air-Sea-Ice Interaction Plenum Publishing Corporation (in press).

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The report summarizes research performed under Contract N00014-76-C-0234, NR 307-252, during the year 1 October 1980 - 30 September 1981. Research topics include: (1) growth of ice in a wave field, (2) large scale heat exchange and ice production, (3) interaction of solar radiation with the ice and upper ocean, (4) optical properties of ice and snow, (5) generalized radiative transfer modeling, (6) wave propagation and other phenomena near the ice edge.

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